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NEW DEVELOPMENTS IN VACUUM MICROELECTRONICS

by

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Abstract: This paper describes a new field-vacuum microelectronics or vacuum integrated circuits (VIC). Its principle, the structure of the field emission microtriodes and microfabrication techniques and processing are given in detail. The processing for the thin field emission cathodes is also reviewed. The application of VIC and the related problems for its future development are discussed.

I. Introduction

In recent years, vacuum microelectronics has seen new growth and tremendous new development. The emergence of this new field undoubtedly will bring to the old field of vacuum electronics great transformation. It will also influence the application and development of the whole subject of electronics. Microelectronics deals with fabrication of integrated micro vacuum tube or vacuum integrated circuits (VIC) on a wafer using the state-of-art microfabrication techniques. By the mid-1980s, it is already possible to fabricate 10,000 micro vacuum tube on a $1mm^2$ area[1]. This technology has attracted attention and interest from the science and technology domain abroad. In June of 1988 and July of 1989, the first and second international conference on vacuum microelectronics were held at Williamsburg, USA and Bath, England. The third international meeting was held in July of this year at Monterey, USA. These meetings have greatly energized the development of this research work.

The emergence of microelectronics is not accidental. It is the inevitable result of the advancement in microfabrication, semiconductor technology and vacuum electronics technology[2]. As early as in 1961, Shoulder of Stanford Research Institute (SRI) has proposed micro vacuum field emission tube[3]. This idea has resulted a new type of low voltage, high electric density field emission cathode - Spindt cathode[4]. With the continued improvement and advances in microfabrication techniques, field emission cathodes of larger area and higher electric density can be manufactured. They have been used in various types of vacuum components including microwave tubes[5-14].

The rapid advances in computer speed have stimulated the development of high speed semiconductor units. However, the further enhancement of the speed of the unit is restricted by the inherent characteristics of semiconductors. Due to the scattering of photons and electrons, the migration speed of the carrier in the semiconductor is less than 5 $\times 10^7$ cm/s[8,9]. To find new ways to improve the unit switching rate, people have reassessed the motion of electrons in a vacuum and in a semiconductor and concluded that the speed of electrons in a vacuum can theoretically reach the speed of the light, i.e. 3 $\times 10^{10}$ cm/s, and in practice it can reach 6~9 $\times 10^8$ cm/s. It can be said that, the reason why semiconductor components have gradually replaced vacuum tubes in the field of data and signal processing in the past 30 years is not because that the semiconductors are better media than vacuum for electron migration, but because that the working principle and fabrication techniques of semiconductor components as such that they can be made very small in size, small in power dissipation, and can be batch produced repeatedly. On the other hand, the fabrication of vacuum tubes relies on machining and manual assembling. Hence the gap between the electrodes is three magnitude bigger than the size of semiconductor units made by light scribing techniques. This limits the switching rate and electron migration time of vacuum electronic units. Worse still, the heated cathode is used as the source of electrons, which results in higher power dissipation; furthermore the spatial

charges in front of the cathode causes the electrodes to work under very higher voltage in order to extract useful electron beam.

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The development of field emission cathode allows us to envision that if we use field emission cathode lattice to fabricate vacuum microtriodes or vacuum integrated circuits, the size of the circuits can be made as small as that of the semiconductor units. The high electric field in front the emitter causes the spatial charge effect to disappear. The speed of the electron carrier is much higher than the speed of the semiconductor carrier. There are reasons to believe that, using microfabrication techniques, units built on bases of field emission lattice charge emitter and vacuum migration can become the fastest units among all switching units.

II. Vacuum microelectronic components

Early computers used to use two vacuum triodes to form a switching circuit as a memory unit. In modern computers, they have been replaced by integrated circuits. A single wafer can contain tens of thousands memory units. In order to increase the memory units on a single wafer and to reduce power dissipation, the size of the circuit has kept decreasing. The line width of 1 μm has become regular processing. Techniques of 0.5 μm processing will soon become the standard. To increase the switching rate of the semiconductor units, alloy materials such as Gallium Arsenide and Phosphorus Indium have been used because the electron migration speed among these materials is higher than that in a silicon material. However, even among these alloy materials, the electron migration speed is still limited. This motivates us to reassess the transmission of electrons in a vacuum. According to the proposal by Shoulder and using the field emission cathode fabrication technique due to Spindt[3,4], it is possible to form a type of field emission microtriode (see Fig. 1). This kind of triodes consist of a metallic cone used as the cathode, which is attached to a metal or highly conducting semiconductor bottom

electrode. The height of the cone is h and the tip radius is r. The distance from the anode to the tip of the cathode is d. The screen has a radius of a and a thickness of t. The tip of the cathode lies in the center of the screen hole. When the screen has a positive voltage relative to the bottom electrode, there is a very strong electric field near the tip of the cathode. If the strength of the electric field exceeds 5×10^{7} V/cm, due to the tunneling effect, electrons will escape from the metal and enter into the vacuum. The number of electrons emitted by the cathode will be controlled by the strength of the electric field near the tip of the cathode or the voltage on the screen grid[15,16].

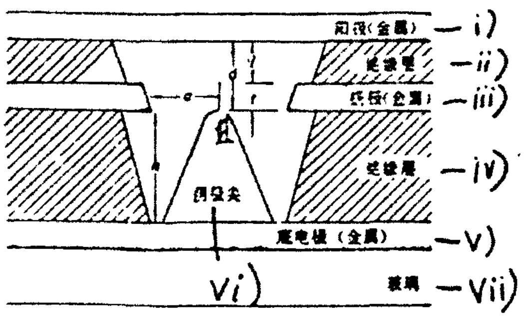

Fig. 1 Field emission vacuum microtriode.
i) Anode (metal). ii) Dielectric layer. iii) Screen grid (metal). iv) Dielectric layer. v) Bottom electrode (metal). vi) Cathode tip. vii) Glass.

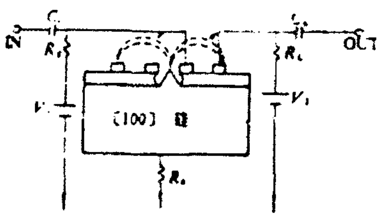

Fig. 2 Vacuum field emission transistor (VFET)
i) Silicon.

Gray et al. have used field emission lattice to make a type of vacuum field emission transistors (Fig. 2). This type of transistors use n-type <100> silicon wafer with doping concentration $10^{15}/cm^3$ as base electrode. Pyramid shaped field emitter is formed by orientation dependent etching (ODE). Silicon layer of thickness 1-2μm is used as the dielectric layer. On the dielectric layer, a metal strip of 0.5 μm thick and 20 μm wide is etched as the screen grid. Remove the dielectric material near the field emitter to form a circular hole of size 1-2 μm. Place a similar metal strip outside the screen grid to form the collector. This is what the complete vacuum field transistors are made of. Electrons will follow projectiles in the vacuum to travel from the cathode to the collector, unlike the transmission through the gap inside a solid state component.

In designing the vacuum microtriode, the following factors should be taken into consideration[15]:

1. With regard to the gap between the electrodes and the vacuum degree.

The distance of movement of the electrons, d, from the cathode to the collector must be less than the mean free path λ_e, i.e.

$$d < \lambda_e. \qquad (1)$$

The mean free path of the electrons is

$$\lambda_e = \frac{T}{273\ p\ P_c(V)}\ (\mathrm{cm}), \qquad (2)$$

where $P_c(V)$ is the probability of collision between the electrons and the residue gas molecules, i.e. the number of collisions resulting from electrons of velocity v ($v = (2eV/m)^{1/2}$) moving 1 cm at 0°C and 1 torr pressure; T is the absolute temperature in K; p is the gas pressure in torr. Fig. 3 gives the measured collision probability of common gases at atmospheric pressure. The electrons possess energy which is equivalent to the ionization voltage. Table 1 gives the mean free path of electrons among these gases. The dependence of collision probability upon the distance is given in the following formula.

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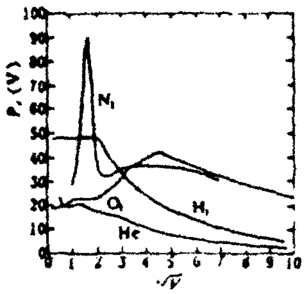

Fig. 3 The relationship between the collision probability of electrons among common gases and the energy.

Table 1 The mean free path of electrons among various gases. The pressure of the gases is the atmospheric pressure. The electrons possess energy which is equivalent to the ionization energy. i) gas. ii) the first ionization voltage. iii) λ_e value at V_i.

ii) iii)

i)

气 体	第一电离电压 V_i (eV)	$P(V_i)$	在V_i时的λ_e
He	24.6	9	1.56
O_2	12.5	35	0.40
N_2	15.6	40	0.35
H_2	15.4	27	0.52
H_2O	12.7	70	0.20

$$P(x)=1-e^{-x/\lambda_e} \approx x/\lambda_e \qquad x/\lambda_e \ll 1. \qquad (3)$$

If we only allow 1% electron collisions so that the unit can function, from formula (3) we will get

$$d \le 10^{-2}\,\lambda_e.$$

In order that the screen grid can have an effective control over the electric field near the tip of the cathode, we need

$$a \le d \qquad (4)$$

Today's technology permits a ≈0.5 μm, therefore we let a equal 0.5 μm. Units with a distance like this between the electrodes can function satisfactorily at 10^{-3} atmospheric pressure (or 1 torr).

To prevent the breakdown of the vacuum between the screen grid and the anode, the following formula must be satisfied:

$$E_a = \frac{V_a - V_g}{d} < 5 \times 10^5 \text{ V/cm} \qquad (5)$$

because when the electric field exceeds 5×10^5V/cm, breakdown will occur.

2. Migration time

In Gallium Arsenide, Indium Phosphorus and silicon these three semiconductors, the peak value of the electron migration speed approaches 2×10^7 cm/s. The time needed to pass a gap of 0.5 μm is 2.5×10^{-12}s. The migration time of electrons among a uniform electric field is

$$t=\left[\frac{2d^2m}{V_a e}\right]^{1/2} \qquad (6)$$

When $d = 0.5\mu m$, V_a=20V, $t = 3.8 \times 10^{-13}$s, Fig. 4 gives the comparison of electron migration time among semiconductor units and vacuum microelectronic units.

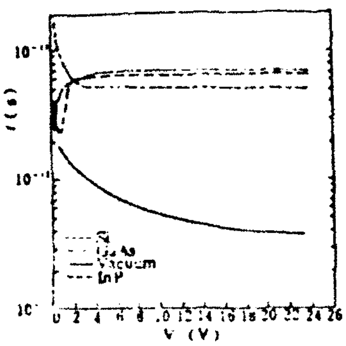

Fig. 4 The relationship between the migration time t and the electrode voltage at d = 0.5 μm.

3. Power capacity

Using microfabrication method, it is possible to make large scale vacuum microtriode array. Two units can form a switching circuit as a memory unit. To check if the current is flowing in the circuit, it is sufficient to supply 10^{-5}A current to the cathode tip at the rate of hundreds giga pita[15]. If the anode voltage is 20 V, the power dissipation of a pair of triodes is 2×10^{-4} W. On each square centimeter there are 10^4 memory units, hence the power dissipation is $2W/cm^2$. If the number of circuits is increased to 10^6 $/cm^2$, it will become necessary to use cooling

technology and to lower the voltage of the electrodes. To do that, the sizes of the electrode a and d will have to be further reduced.

III. Thin film field emission cathode

Thin film field emission cathode is the core technology of vacuum microelectronic circuits. This technology was first proposed by Spindt after studying micro field emitters[3,4]. The field emission cathode possesses the characteristics of low voltage and high current density; the emission of electrons are accomplished by utilizing the tunnelling effect under high electric field which allows electrons inside the metal to pass the surface and to enter into the vacuum. Hence no heating is needed. This feature allows it to have wide application potential among various vacuum electronic components. With the advancement in microfabrication techniques, the fabrication techniques of this type of cathodes also advance[7-14,16-22]. The key technology lies in orientation dependent etching (ODE).

1. Orientation-Dependent-Etching

Silicon materials have the diamond cubic crystal structure. In this structure, there are a few low index crystal faces which can be used to fabricate semiconductor units of special structures.

2. Thin film field emission cathode (TFFEC) lattice

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The thin film field emission cathode made by Spindt is shown in Fig. 5. It has a sandwich structure consists of conductor/dielectric layer/conductor. The screen grid on the top has a circular hole of diameter 1 ~ 3μm. Through this hole, it is possible to etch away the dielectric layer to form a chamber. A metal cone is firmly attached to the bottom electrode. The tip of the cone is situated in the center of the circular hole of the screen grid. Use silicon with heavy doping as the substrate. Grow a layer of SiO_2 of 1 μm thick as the insulation layer. Since SiO_2 is very tight, it has a high breakdown resistance. A layer of molybdenum film of thickness 0.5 μm is vapor deposited on the SiO_2 as the screen grid. The height of the cone, the radius of the cone

tip and the diameter of the screen grid can be changed in order to control the voltage and current characteristics of the cathode. The fabrication methods of the cathode array are in the following[4,12,13]:

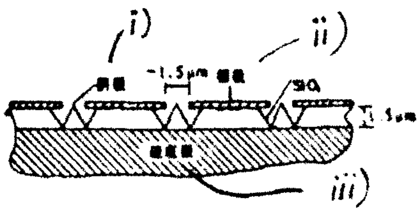

Fig. 5 Spindt cathode. i) cathode, ii) screen grid, iii) silicon base plate.

(1) Use a 0.75mm thick, highly conducting (0.01Ω/cm) standard 5 cm diameter silicon wafer as the base plate

(2) Apply the standard oxidization method to grow a layer of SiO_2 of thickness 1.5μm on the base plate.

(3) Use electron beam vaporization or vacuum vaporization method to deposit a layer of molybdenum film of thickness 0.5 μm on the SiO_2 layer.

(4) Use the standard rotation coating method to apply a layer of electron beam etching glue PMM (Poly-Methyl-Methacryate) with approximate thickness 1 μm on the molybdenum film.

(5) Use electron beam etching, electron beam radiation to form two kind of lattices with gap widths 25.4 μm and 12.7μm. The diameter of each point is 1μ.

(6) Remove the PMM glue irradiated by the electron beam to expose the molybdenum film there. Afterwards, etch away the molybdenum film being exposed to reveal the SiO_2 layer.

(7) Remove the remaining PMM. Use HF to etch SiO_2 until the silicon substrate is exposed. This will form the structure shown in Fig. 6a.

(8) Fix the silicon wafer in a vacuum deposition system so that the substrate rotates along its center axis. Choose an appropriate deposition orientation and deposit an aluminum layer so that diameter of the tip circular hole can be controlled to required small size (Fig. 6b).

(9) Use a small vaporization source lying above the inlet hole and apply the electron bean vaporization method to deposit molybdenum into the partially sealed inlet hole. As molybdenum accumulates, the inlet hole becomes smaller. Inside the chamber, the molybdenum forms a cone. When the inlet hole last seals, the cone will have a sharp tip. The height, angle and the tip diameter of the cone are determined by, the diameter of the inlet hole at the beginning of the molybdenum deposition, the thickness of the dielectric layer and the distance between the vaporization source and the substrate.

(10) Remove the aluminum film and the molybdenum deposited during the forming of the cone. The fabrication of thin film cathode is complete.

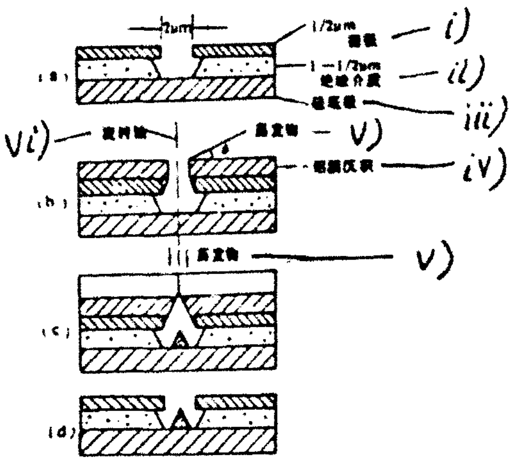

Fig. 6 The fabrication procedure of the thin film field emission cathode. i) screen grid, ii) dielectric layer, iii) silicon bottom plate, iv) aluminum film deposit, v) vaporizing substance, vi) axis of revolution.

Thin film field emission cathodes can also be fabricated using orientation dependent etching[10,11,17,20-22].

Fig. 7 shows the fabrication procedures used by Busta et al. to make tungsten-film-silicon-cone field emission cathodes. Place a silicon substrate of (100) lattice in dry oxygen at 1050°C to

grow a layer of oxide of thickness 1200 Å. Afterwards, use light scribing method to etch out island matrices of SiO_2 of square shape. The sides of the square are parallel to the flat cut of the substrate, i.e. parallel to the <110> lattice direction. After removing the light scribing glue, place the silicon substrate in orientation dependent etching fluid (660 ml ethylenediamine, 140g pyrocatechol and 330 ml water). Under 105°C temperature, allow the etching process to last 3.5 minutes to form a pyramid shaped cone consisting of four mutually intersecting (111) lattice faces. The angle between the substrate and the side surface of the cone is 54.7°. Use dilute HF solution to remove the remnant SiO_2 islands. Now the tungsten deposition can proceed.

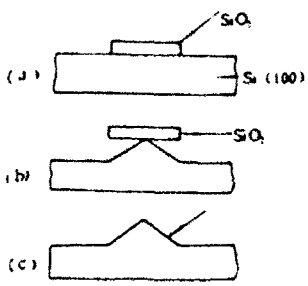

Fig. 7 Fabrication procedures of the tungsten film silicon cone. (a) SiO_2 diagram, (b) Tetrahedral cone formed by orientation dependent etching, (c) fabricated tungsten film cone.

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Tungsten film deposition takes place inside a cold-wall aluminum reactor with dimensions 12 in × 12 in. Inside the reactor there is a heated substrate mounting disk. The carrier and the reacting gas are introduced through a 0.25 in stainless pipe. The inlet pipe is kept 2 in away from the heater and extends upwards for 2 inches. During the reaction, the gas flow passes through the substrate; the discharge is extracted from a pipe at the bottom of the reactor which forms an 180° angle with the inlet pipe. Before the tungsten deposition, the system pressure should reach 1×10^{-5} torr.

Two methods of tungsten film deposition are used. One is the silicon reduction method of WF_6 and the other is the hydrogen reduction method. In the silicon reduction method, argon is used as the carrier gas; its flow rate is 200 sccm. The flow rate of WF_6 is 36sccm. The total pressure is 1torr. Deposition takes place at 325°C temperature and it lasts 5 minutes. A tungsten film of 50 Å with a surface resistance of 110 Ω/. 100 Å silicon is consumed during the reaction process (Fig. 8a).

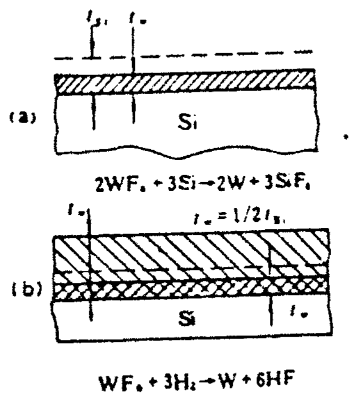

Fig. 8 The formation of the tungsten film. (a) Silicon reduction method. (b) Hydrogen reduction method.

In a hydrogen reduction process, silicon reduction takes place during the earliest stage to convert the silicon at the tip of the cone into tungsten. After a very thin layer of tungsten film has been formed, WF_6 reduction begins. The flow rate of the hydrogen is 1000sccm. The flow rate of WF_6 is 2sccm. The total pressure is 2 torr and the temperature is 325°C. Argon is not used as the carrier gas. Tungsten film of 1200Å, 4 Ω/ can be deposited in 13 minutes.

Why two deposition methods are used? First, the film thickness obtained by the silicon reduction method is limited within 50 ~ 200 Å. This will not change the structure at the tip

of the cathode. Second, during a tungsten reduction process, it is discovered that there is excess fluoride on the top of the tungsten layer; this will change the height of the tunneling potential barrier to affect the emitted current. Third, with the increase of the surface electric resistance of the tungsten film, a resistor can be cascaded to the testing circuit; this can reduce the damage to the tip of the cathode.

3. Cathode emission characteristics

The theory of Fowler-Nordheim[6] gives, for a clean metal surface, the relationship between film emission current density J, the surface electric field E (V/cm) and the work function ϕ(eV)[12]

$$J = \frac{A\ E^2}{\phi\ t^2(y)} \exp\left(-B\ \frac{\phi^{312}}{E}\ v(y)\right) \qquad (7)$$

where, $A = 1.54 \times 10^{-6}$,

$B = 6.87 \times 10^{7}$,

$y = 3.79 \times 10^{-4}\ E^{1/2}/\phi$,

and y is the reduction coefficient of the potential barrier of the Schottky *work function. Under the working conditions of most* cathodes, the approximate formulae can be used for t^2 and v

$$t^2(y) = 1.1 \qquad v(y) = 0.95 - y^2 \qquad (8)$$

Let the emission area of the cathode be α, the conversion coefficient of the cathode surface voltage to electric field be β. Substitute the relations $J = I/\alpha$ and $E = \beta\ V$ into equation (7) to obtain

$$I = aV^2 \exp(-b/V) \qquad (9)$$

where

$$a = \frac{\alpha AB^2}{1.1\phi} \exp\left(\frac{B(1.44 \times 10^{-7})}{\phi^{1/2}}\right) \qquad (10)$$

$$b = 0.95B\phi^{3/2}/\beta. \qquad (11)$$

Fig. 9 shows the cathode Fowler-Nordheim diagram of a single, 100 and 5000 cone shaped arrays. These lines are basically mutually parallel; the gap distances correspond to the ratio of the number of the cone tips. Fig. 10 is the current-voltage characteristic diagram of a cathode with the tip distance 12.7 µm and with 5000 cone tips.

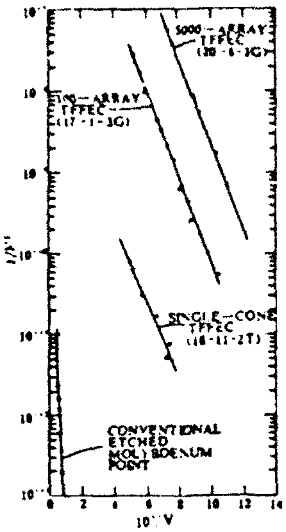

Fig. 9 The cathode Fowler-Nordheim diagram

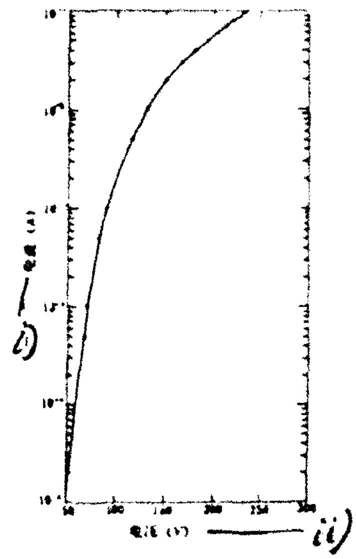

Fig. 10 Cathode current-voltage characteristic of a 500 cone shaped array. i) current, ii) voltage.

IV. Micro integrated vacuum tube

Micro vacuum electronic tube is a switch and control unit. Its structure and technology are similar to that of the previous vacuum tube. The difference lies in the very small size of the unit and it uses field emission cathode to replace the original hot cathode. Orvis et al. have made micro vacuum tubes such as shown in Fig. 1[19,20]. Their structure is shown in Fig. 11 (a).

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The method of fabricating vacuum microtriodes is as follows. The first step is to etch a pyramid shaped field emission cathode on a silicon substrate (shown as B in Fig. 11b), this has been described in the previous section. The second step is to bury the field emission cathode inside a SiO_2 glass doped with phosphorous (shown as C in Fig. 11b); during this process, the glass should be melted to enable it to flow in order to form a flat surface. The third step is to form crystalline silicon strip as screen grid on

the tip of the glass (shown as D in Fig. 11b); there is a screen hole on the strip and the tip of the cathode lies in the center of the screen hole. The fourth step is to form another layer of SiO_2 glass doped with phosphorous on the screen surface (shown as E in Fig. 11b). The fifth step is to form the anode of crystalline silicon (shown as F in Fig. 11b). The structure obtained at this point has an inside filled with glass rather than vacuum. Remove the glass using corrosion to form a micro vacuum triode. A hole can be prepared on the anode beforehand to facilitate the removal of the glass by corrosion. Place the triode obtained this far inside a vacuum system to bake in order to remove the residue gas. At the very last, deposit a layer of metal to seal off the hole on the anode.

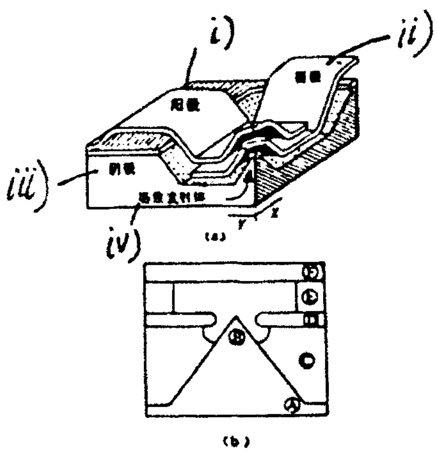

Fig. 11 Structure diagram of the micro vacuum tube. i) Anode, ii) screen, iii) cathode, iv) field emission body.

Itoh and Hiroshima give another microtriode fabrication method[22]. Fig. 12 shows the fabrication procedure of their method. In the first step, splash 4 µm SiN film and 0.1 µm W film on a n-type (100) silicon substrate. In the second step, use SF_6 gas to conduct reaction ionic etching; use HF solution to conduct wet etching; form SiN protective film of 5 µm diameter. In the third step, use orientation dependent etching to form field emission anode of four corner cone; the solution used for orientation dependent etching is KOH:H_2O:Isopropanol = 40:400:100,

under the temperature of 30 ±0.5°C; the etching speed is 26nm/min. Changing the ratio of various components of the solution can affect the etching speed. In the fourth step, use electron beam vaporization method to deposit insulation layer and 0.2 μm thick molybdenum as the screen and the anode respectively; the insulation layer uses a mixture of SiO_2 and Al_2O_3 as vaporization source; the gap between the substrate and the screen is 2 μm and the gap between the screen and the anode is 1 μm. Finally, use ultrasonic vibration method to remove SiN protective film and conduct another orientation dependent etching of the cathode to sharpen its tip. During these fabrication processes, the screen, the anode and the cathode are self centering since they use the same protective film.

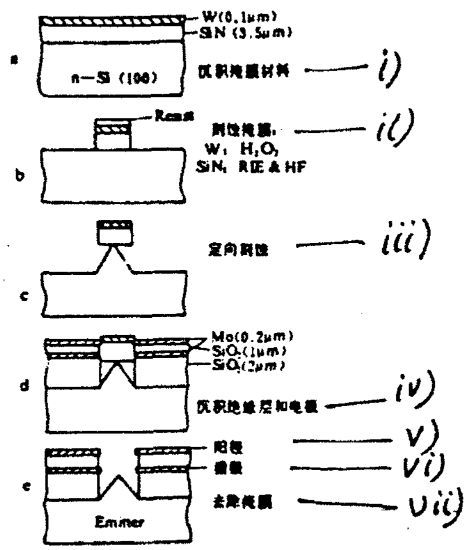

Fig. 12 The fabrication procedure of micro vacuum triodes. i) deposit protective material, ii) etch protective film, iii) orientation dependent etch, iv) deposit insulation layer and the electrode, v) anode, vi) screen, vii) remove the protective film.

Orvis et al. have conducted modelling calculation of the microtriode they made. They use the metal boundary as the boundary condition for the surface of the silicon field emission cathode. This is an approximate condition. Fig. 13 gives partial calculation results. Fig. 13a gives the relationship between ..e

electric field at the cathode tip and the screen voltage. The electric field at the screen is the most important because the screen is not supposed to emit electrons. Fig. 13b gives the trajectories of the electrons emitted from different places of the cathode. When leaving the emitting tip, the trajectories of the electrons are almost straight lines indicating that, in agreement with the experimental result, the current flowing to the screen is small. Though the ionic bombardment is the most severe problem of the field emission, However, based on the simulation results, it is not expected to be serious. This is because of the low voltage of the anode (the V_a there is 150V). In the meantime, the equal potential lines in the region of anode-screen are parallel to the anode; consequently the ions in this region will accelerate towards the screen. Furthermore, since the space between the cathode tip and the screen is small, only small amount of ions are produced.

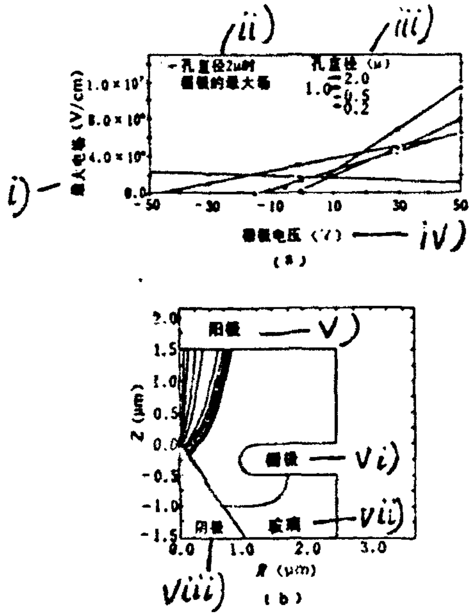

Fig. 13 Results of the microtriode modelling calculations. (a) The relationship between the electric field at the cathode tip and the screen voltage; the voltage of the anode is 150V. (b) The trajectories of electrons emitted from different places on the cathode tip. V_c=0, V_a=150V, V_g=0V. i) maximum electric field, ii) the maximum field at the screen when the diameter of the hole is 2 μm, iii) hole diameter, iv) the voltage of the screen, v) anode, vi) screen, vii) glass, viii) cathode.

Using the simulation data, we can obtain some functioning characteristics of the microtriode. When different voltages are used for the anode and the screen grid, the calculation of the cathode electric field indicates that the variation of the electric field as functions of these voltages is linear. Hence the following formula can be used to describe the relationship between the electric field at the cathode tip and the voltage of the anode and cathode:

$$E = F(2.86\times10^{4}V_{a} + 6.79\times10^{4}V_{s} + 1.16\times10^{5}) \quad (12)$$

where V_a is the anode voltage, V_s the screen voltage, E the electric field, F the adjusting coefficient adopted so that the result of formula (12) agrees with the experimental result whose typical value is 10 ~ 100.

V. Conclusion

The development in micro fabrication techniques and in field emission cathodes has ushered in the rise of a new discipline - vacuum microelectronics. The biggest advantage of vacuum integrated circuits is their ability to withstand working environment of high temperature, high strength radiation, which enables them to have important applications in measurement of nuclear reactors, in space system and in deep earth exploration. Since the electrons move inside a vacuum, the units can obtain high switching characteristics; consequently they can be used in high speed censor, communication and data processing systems.

The wide range of research and exploration has just started. The future of these units depends on whether it is possible to fabricate stable, reliable, and high current density electron emitting sources. This not only requires precise, repeatable fabrication techniques, but also demands deep understanding of the transmission process of electrons inside the vacuum, the semiconductors and the boundary of the two under high electric field. This new field of technology has lead to the development of non-equilibrium physics, the charge transmission under high electric field, the interaction between the electron beam and the

electric magnetic field in microstructure, new material and thin film, new components and circuits, and new application research. It is believed that in the near future, this new discipline will lead to new industrial production and new markets.

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